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ORIGINAL ARTICLE

Idiopathic scoliosis and balance organisation in seated position on a seesaw

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Abstract The aim was to determine the biomechanical processes involved in postural regulation when self-imposed disturbances occur in the seated position in the antero-posterior direction. Twelve female adolescents with right thoracic scoliosis (SG) (Cobb = 30.4° ± 9.7) and 15 control adolescents (CG) were included in this study. The ground reaction forces (GRF) were studied whilst the subjects maintained their balance in the sitting position on a seesaw. Six conditions were tested: eyes open and closed; with an additional load placed on the subject's right or left shoulder; and with an additional load on the subject's right or left pelvis. The SG showed significantly higher force amplitudes and variability and fewer oscillations than the CG in all the conditions. In the SG, the time analysis showed that the duration of the GRF was significantly higher in forward and left directions. Whatever the condition tested, the intra-group differences were not significant. The scoliotic patients in seated position were characterised by larger changes of the GRF, especially with a postural control in the forward and left directions, corresponding to that on the concave side of their spinal curvature. No significant differences were found to exist between the various conditions (load and unload, eyes open and eyes closed). Clinical tests and rehabilitation methods should include assessments of seated patients' spatio-temporal adaptation to GRF.

Keywords Idiopathic scoliosis · Ground reaction forces · Planes · Postural control · Seated balance

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Introduction

Adolescent idiopathic scoliosis (AIS) is a progressive growth disease that affects the spinal anatomy, mobility and left–right symmetry [2, 16]. Consequently, AIS should modify posture and locomotion. In the processes underlying the control of scoliotic patients' postural balance, specific sensory factors may lead to the development of adaptive strategies [23] The specific postural strategies occurring in AIS have been previous studied during upright stance[7] step initiation [4], walking [9] and side-stepping [5]. Scoliotic patients show a characteristic increase in the amplitude of the postural oscillations [20] associated with a larger than normal excursion of the centre of pressure [7] and the centre of mass [19]. This dynamic adaptive motor process has also been found to be associated with an increase in the asymmetry of the dynamic parameters analysed between the two lower limbs [3, 15, 22]. The variability of the parameters analysed was greater in scoliotic patients than in control subjects [5], especially in the medio-lateral (ML) and antero-posterior (AP) directions [13, 23]. The value of the ground reaction forces (GRF) also increases significantly in these patients [5]. The dynamic strategies observed have been found to result in slower movements during walking, balancing on a beam and side-stepping [4, 17]. Very few studies have focused, however, on seated scoliotic patients' balance strategies. This postural situation seems to be worth studying, because it makes possible the neglect of the activity of the lower limbs and isolation of the trunk from the functional point of view. The data obtained on seated subjects so far are rather contradictory. Some authors have reported that spinal deformation is associated with less variability of the centre of pressure shift [21] and less asymmetry between left and right displacements [1] in the seated position. Other authors' findings on the effects of the type of curvature [24] did not confirm the latter conclusion, however, since they showed that the variability and asymmetry increased, on the contrary, in seated scoliotic patients. In the sitting position, the lateral displacement [21], spinal muscle activity [14] and ischial thrust [24] are in fact significantly larger on the convex side of the deformation than on the concave side. Chockalingam [9] has described a special process in scoliosis patients possibly resulting from the asymmetric body masses. The stability of seated AIS patients' postural control in comparison with that of control subjects is therefore a key topic for understanding scoliosis is general, although this topic has given rise to some controversy in literature.

In view of the dynamic strategies previously observed during step initiation and lateral stepping tasks [4], it was proposed to focus here on the postural control of the spine, so as to be able to determine the adaptive processes at work in this segment without having to take the compensatory behaviour of the lower limbs into account. From the mechanical point of view, the adaptive processes at work in scoliotic patients have been found to result in a significant increase in the ischial thrust on the convex side in patients with left lumbar scoliosis in comparison with control subjects [24].

Since the asymmetry of the body masses resulting from spinal deformation leads to developing specific postural strategies, it was assumed here that asymmetrical trunk loading would lead to changes in the behavioural strategies used depending on the position of load on the concave or convex side (frontal plane). Seated position with antero-posterior destabilisation allows analysing scoliosis consequences during control motor strategies on specific trunk organisation in the usual locomotor plane. The aim of the present study was therefore: (1) to investigate the biomechanical factors involved in the postural responses of seated scoliotic patients to an angular acceleration of the seesaw, and (2) to elucidate the resulting strategies by increasing the asymmetry of the mechanical parameters involved by adding specific loads to the subjects' trunk.

Materials and methods

Twelve female adolescents with right thoracic AIS (without compensatory lumbar curves) and 15 control adolescents were included in this study. The control subjects were recruited during a campaign carried out at a lower secondary school, where the experiment and its implications were explained to the pupils. The scoliotic patients were recruited at a children's spinal rehabilitation ward (CHU Bellevue, Saint Etienne, France) by a rehabilitation specialist, who assessed the stage of right thoracic AIS using Cobb's method (Cobb angle = 30.17° ± 9.7, range 19°–45°). The mean gibbosity of the thoracic curvature was 10.16 ± 2.7 cm, and Risser's test gave a mean value of 1.4/5 ± 0.6. The patients had no associated pathologies and the origin of their scoliosis was unknown. The only treatment they were undergoing was wearing a corset and regular physiotherapy (the corset was worn during the daytime and/or at night: it had been worn prior to these experiments for 7 months on average). None of the patients had undergone any surgical treatment. The two groups of subjects were matched in terms of age (control group 13.04 ± 0.8 years, scoliotic group 11.83 ± 0.8 years), height (control group 159.47 ± 5.46 cm, scoliotic group 155.58 ± 4.9 cm) and weight (control group 48.27 ± 7.54 kg, scoliotic group 41.92 ± 8.9 kg). Once the experimental procedure had been validated and all the subjects (who were volunteers) duly informed, they and their legal representatives gave their prior consent in writing.

The experiments were carried out at a hospital functional exploration department or at school. All the experimental procedures were carried out using the same experimental setup. All the tests were performed by the patients without their brace (we asked the patient to leave out the brace, a minimum of 4 h before the experiment).

Dynamic analyses were performed by recording the signals obtained from an AMTI® force platform (PF) installed underneath a seesaw placed on a table (Fig. 1). The reaction forces (RFs), AP (Fx), ML (Fy) and vertical (Fz) forces were recorded at an acquisition frequency of 500 Hz. The seesaw used, which was specially designed for testing seated subjects' equilibrium, consisted of three parts: a plateau that could be fixed in two perpendicular planes with a curve (Fig. 1). Anthropometric measurements were carried out on 72 subjects to define the radius of curvature of the 300 mm-long seesaw plateau ($r = 0.91$) corresponding to the destabilisation of the spinal segment when the axis of rotation was centred on the vertebral level T11 in the case of a subject of 150-cm height. Lastly, a mechanical device was developed to block the plateau of the seesaw in the horizontal position so as to be able to

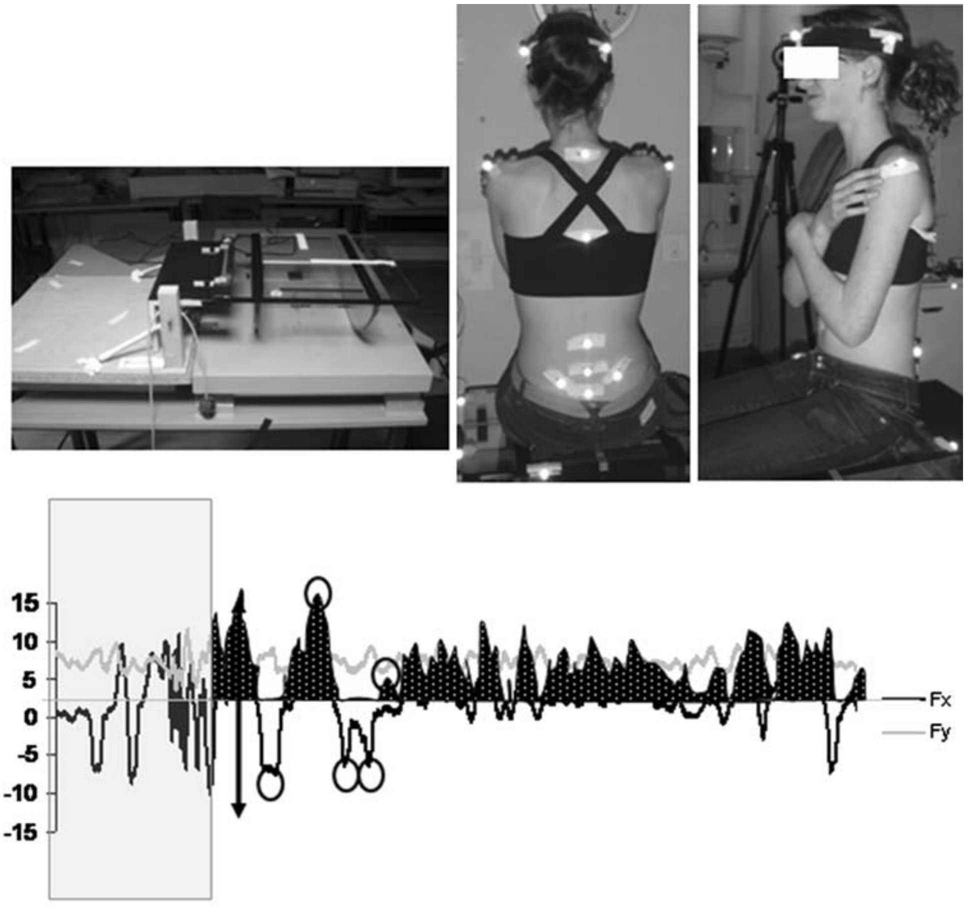

Fig. 1 The experimental setup and data analysis. The *top panel* shows the experimental setup, consisting of a force platform, a seesaw and a destabilising device. The *bottom panel* shows the changes with time (ms) in the ground reaction forces recorded in response to antero-posterior (Fx) and medio-lateral (Fy) perturbations. The performance index (PI) is the area under the curve (*black dotted line*); the frequency is given by the number of oscillations (*circles*) divided by the duration of the movement (ms), the delta value is the maximum value of the force displacement minus the minimum value (*arrows*), and the time spent on the right or left is given by the respective parts of the curve on both sides of the mean line

control the onset of the postural disturbance (t_0) applied to subjects in the sitting position (Fig. 1).

The subjects' foot laterality (dominant limb and non-dominant limb) was determined by applying a push from behind, which triggered a forward stepping movement by the dominant limb. In this way, the leading foot was found to be the left foot in 25% of the subjects and the right foot in 75% of the subjects.

At the beginning of each test, the subject was seated on the seesaw stabilised in the horizontal position, using a special external device (Fig. 1) designed to keep it in a fixed position at the beginning of the test and release it when required. The force signals were recorded from the moment (t_0) the seesaw was released by the experimenter, so that the subject was destabilised in the antero-posterior (AP) direction. The task consisted of keeping balance for 10 s. The experimental conditions were run in randomised order and each condition was repeated three times. The conditions involved the use of visual cues (eyes open, EO vs. eyes closed, EC) and the asymmetrical loading of the shoulder (left shoulder, LS vs. right shoulder, RS) and the pelvis (right pelvis, RP vs. left pelvis, LP). The load added, which corresponded to 15% of the weight of the body segment in question [10], was that found to increase the inertia of the trunk segment in walking scoliotic subjects. Vernazza et al. [25] have suggested that this increase in the segmental inertia may be due to a combination of age and parameters such as body weight, segment weights and segment length. A 0.50-kg load was therefore placed in the latter study [11] on the shoulders and a 2-kg load on the trunk of 10-year old subjects (mean weight 36 kg), and a 0.7-kg load on the shoulders and a 3-kg load on the trunk of 14-year-old subjects (mean weight 56 kg). To increase the mechanical effects of asymmetrical loading, weights that were at least 1 kg heavier than these values were used in the present tests.

The force platform data obtained were processed (using MATLAB v.6, Matworks) to determine the following normalised force parameters: the area under the curve (the postural performance index, PI), the oscillation frequency, the duration of the excursion of each force (right vs. left and forward vs. backward), the delta value of the forces (the difference between the maxima and minima) and the variability of the forces. Correlations were also calculated to measure the interactions possibly occurring between the changes in the Fx and Fy data (Fig. 1).

With each parameter calculated, the normality of the data dispersion was checked by performing a Shapiro–Wilk test. The statistical validity of the hypotheses adopted was tested by performing an analysis of variance (ANOVA, Statistica, v.6, Statsoft). A threshold value of $p < 0.05$ was adopted for ruling out the null hypothesis. Lastly, interactions were measured a posteriori by performing a Newman–Keuls test to check the occurrence of specific effects. Correlation tests were performed to characterise the changes in the Fx and Fy parameters with time.

Results

Keeping balance: the number of falls

In all the trials, the scoliotic patients were characterised by a significantly larger number of falls than the control subjects (mean number of falls per scoliotic patient: 0.8 ± 1.21 versus 0.0 ± 0.0 in the control subjects, $p < 0.05$, Fig. 2).

Antero-posterior balance

Comparison between scoliotic and control groups

In the case of the Fx data, the PI showed a significant increase in the forward direction in the scoliotic group in all the experimental conditions ($9{,}878 \pm 6{,}769 < \text{PI} < 11{,}206 \pm 9{,}218$ vs. $4{,}767 \pm 4{,}896 < \text{PI} < 5{,}745 \pm 3{,}484$ in the control group, $p < 0.03$) except for condition RS. In the case of the Fy data, the PI (on both the left and right sides) did not differ significantly between the two groups in any of the experimental conditions.

The mean reaction force frequency of Fx responses did not differ significantly between the two groups, whereas that of the Fy responses was significantly higher in the scoliotic patients ($8.06 \pm 1.93 <$ frequency $< 8.80 \pm 2.88$ vs. $6.21 \pm 2.01 <$ frequency $< 6.75 \pm 1.45$ in the control group, $p < 0.05$), except in conditions RP and LP.

The time analysis showed that the duration of the reaction force excursion was significantly higher in the forward direction in the scoliotic subjects in conditions EO ($55 \pm 8\%$ of the time was spent in the forward direction vs. $51 \pm 10\%$ in the case of the control subjects, $p < 0.05$) and RP ($55 \pm 6\%$ of the time was spent in the forward direction vs. $47 \pm 14\%$ in that of the control subjects, $p < 0.03$), whereas the duration of the force reaction excursion to the left was longer in the scoliotic patients in all the conditions tested ($56 \pm 10\% <$ "left time" $<57 \pm 9\%$ vs. $48 \pm 5\% <$ "left time" $<51\% \pm 14$ in the control subjects, $p < 0.01$, Fig. 3).

With both parameters Fx and Fy, the delta values were significantly higher in the scoliotic group than in the control group in all the conditions tested (Tables 1, 2). In parallel, the patients obtained significantly higher minimum Fx and Fy values and maximum Fx values. In all the conditions tested, the timing of the extreme Fx and Fy values (the maxima and minima) was significantly increased in the control group than in the scoliotic group (Tables 1, 2). The variability of the Fx and Fy data was also found to be significantly greater in the scoliotic patients than in the control subjects (Tables 1, 2).

In both groups, the correlations between force components AP and ML were found to be non-significant.

Comparison between conditions

No significant differences were found to exist between the various conditions, EO, EC, LP, RP, RS and LS, tested with either of the forces Fx or Fy in either group (the scoliotic or control group), (Tables 1, 2).

Discussion

The data obtained make it possible to describe the postural strategies adopted by the two groups studied to deal with AP perturbation in a seated position. The scoliotic patients were characterised by larger changes in the ML and AP components of the GRF, especially with a postural control in the forward and leftward directions, corresponding to the concave side of their spinal curvature. This feature may be attributable to the delayed

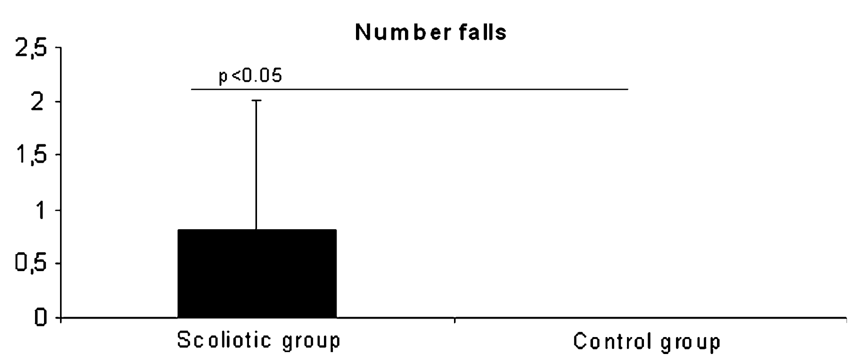

Fig. 2 Mean number of falls per subject in the control group and the scoliotic group. Significant differences ($p < 0.05$) are indicated by a *black horizontal line*

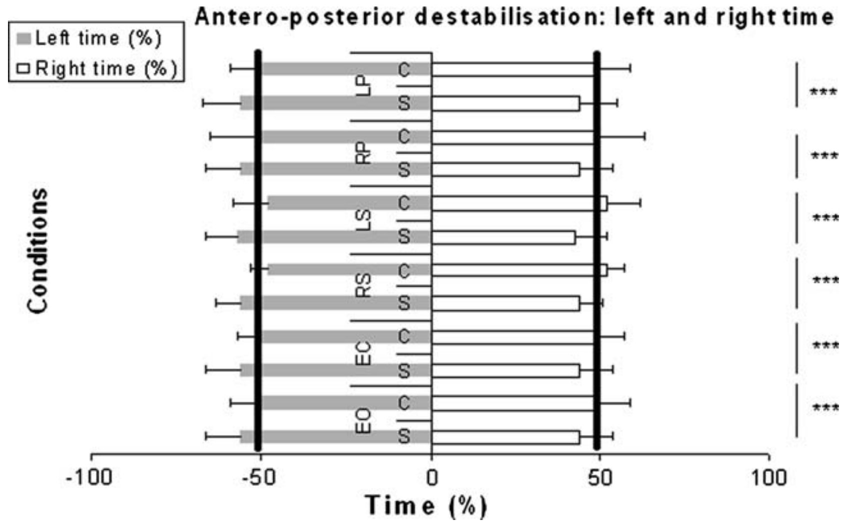

Fig. 3 Antero-posterior destabilisation. Time spent on the right and left (as percentages) in the following conditions: eyes open or closed (EO and EC), right or left shoulder loaded (RS and LS) and right or left pelvis loaded (RP and LP). Results obtained with the control group (C) and the scoliotic group (S). Significant differences ($p < 0.01$) are indicated by *three asterisks*

Table 1 Antero-posterior destabilisation: Fx (antero-posterior component of ground reaction force)

	EO	EC	RS	LS	RP	LP	*p*
Min							
S	−15.56 ± 16.39	−11.81 ± 12.33	−14.62 ± 12.94	−11.92 ± 14.07	−14.56 ± 11.11	−11.62 ± 10.76	NS
C	−3.73 ± 2.35	−3.68 ± 2.41	−5.72 ± 4.22	−3.52 ± 2.07	−4.41 ± 4.51	−3.54 ± 3.44	NS
	***	***	***	***	***	***	
Occ_Min							
S	1,576 ± 783	1,518 ± 534	1,450 ± 518	1,335 ± 245	1,591 ± 756	1,359 ± 251	NS
C	3,749 ± 2,485	4,131 ± 2,251	3,372 ± 2,337	3,757 ± 2,368	3,224 ± 2,053	3,956 ± 2,478	NS
	***	***	***	***	***	***	
Max							
S	11.26 ± 12.14	11.62 ± 11.65	10.57 ± 13.29	10.82 ± 9.97	13.50 ± 14.90	11.89 ± 11.07	NS
C	3.72 ± 2.20	3.68 ± 2.06	5.27 ± 4.12	3.76 ± 2.63	4.09 ± 4.34	3.68 ± 4.37	NS
	**	**	***	**	***	***	
Occ_max							
S	1,837 ± 816	2,376 ± 1,947	1,897 ± 987	1,644 ± 737	1,928 ± 1,028	1,810 ± 886	NS
C	3,354 ± 2,264	3,955 ± 2,356	3,600 ± 2,319	3,687 ± 2,260	3,222 ± 2,009	4,377 ± 2,438	NS
	**	**	***	***	**	***	
Delta							
S	26.82 ± 23.21	23.43 ± 16.54	25.19 ± 17.18	22.75 ± 14.91	28.06 ± 19.50	23.51 ± 14.91	NS
C	7.46 ± 4.27	7.36 ± 4.25	11 ± 7.47	7.28 ± 4.39	8.53 ± 8.55	7.22 ± 7.74	NS
	***	***	***	***	***	***	
Variability							
S	2.75 ± 2.66	2.64 ± 2.57	2.58 ± 2.42	2.48 ± 2.23	2.98 ± 2.53	2.63 ± 2.25	NS
C	1.07 ± 0.64	1.04 ± 0.54	1.47 ± 0.94	0.97 ± 0.57	1.09 ± 0.97	1.00 ± 0.92	NS
	***	***	**	***	***	***	

Significant differences are accepted for *p* values <0.03 (**) and <0.001 (***). NS not significant *p* value >0.05

timing of the performances observed in these same directions. No differences between conditions were observed in either group during AP destabilisation, thus loading the pelvis, loading the shoulders and the presence/absence of visual cues had no effect on the subjects' balance strategies. The limited statistical results may be the consequence of the restricted number of patients (i.e. 12), but may also be due to the lateral positioning of the load, which privileged the frontal plane despite the movement being orthogonal! Our results revealed the existence of a strategic behaviour constant in the scoliotic group, whatever the condition.

Table 2 Antero-posterior destabilisation: Fy (medio-lateral component of ground reaction force)

Min							
S	−5.93 ± 6.38	−5.57 ± 6.21	−5.11 ± 6.05	−5.13 ± 6.49	−5.72 ± 6.03	−5.93 ± 6.03	NS
C	−2.21 ± 0.83	−2.15 ± 1.18	−2.51 ± 1.10	−2.19 ± 1.15	−2.4 ± 1.26	−2.51 ± 1.44	NS
	**	**	**	*	**	**	
Occ_Min							
S	2,122 ± 1,794	2,300 ± 2,124	1,946 ± 1,703	1,905 ± 1,414	1,811 ± 1,261	1,418 ± 420	NS
C	4,437 ± 2,298	5,239 ± 1,916	4,845 ± 2,587	4,178 ± 2,336	4,367 ± 2,399	4,349 ± 2,444	NS
	***	***	***	***	***	***	
Max							
S	4.04 ± 6.25	3.84 ± 5.52	4.09 ± 5.11	4.38 ± 5.12	4.06 ± 5.17	4.00 ± 5.02	NS
C	2.3 ± 0.87	2.21 ± 1.01	2.41 ± 0.99	2.38 ± 1.26	2.27 ± 1.33	2.5 ± 1.37	NS
	NS	NS	NS	NS	NS	NS	
Occ_max							
S	1,606 ± 711	2,560 ± 2,013	2,541 ± 2,276	2,696 ± 2,247	1,960 ± 1,780	2,065 ± 1,944	NS
C	4,134 ± 2,313	4,281 ± 1,965	4,445 ± 2,391	4,388 ± 2,106	4,476 ± 2,341	4,264 ± 2,472	NS
	***	**	**	**	***	***	
Delta							
S	9.98 ± 5.21	9.42 ± 4.51	9.21 ± 3.21	9.52 ± 3.98	9.78 ± 2.90	9.93 ± 3.14	NS
C	4.51 ± 1.59	4.36 ± 2.09	4.92 ± 1.92	4.56 ± 2.27	4.67 ± 2.45	5.03 ± 2.67	NS
	***	***	***	***	***	***	
Variability							
S	1.08 ± 0.62	1.14 ± 0.67	1.09 ± 0.62	1.14 ± 0.64	1.11 ± 0.57	1.05 ± 0.50	NS
C	0.64 ± 0.25	0.61 ± 0.27	0.72 ± 0.29	0.66 ± 0.32	0.65 ± 0.30	0.64 ± 0.34	NS
	***	***	**	***	***	***	

Significant differences are accepted for p values <0.05 (*), <0.03 (**) and <0.001 (***). NS not significant p value >0.05

Although it has been reported in some studies on seated posture that scoliotic patients' equilibrium was more stable than that of the control subjects [1], the dynamic spinal stabilisation performances observed here show on the contrary that scoliotic patients run a greater risk of falling than control subjects. Subjects who fell were asked to repeat the task, which introduced learning effects, but despite the larger number of trials run because of falls, significant differences persisted between the groups as previously observed in studies on walking and the standing position [9, 20]. The reason why the patients fell more frequently may be that the maximum amplitude of the GRF was reached earlier, possibly because of a postural integration deficit making fast stabilising reactions difficult. However, the present AIS patients managed to control their postural responses to destabilisation after several trials, thanks to the effects of learning. This learning effect does not modify the motor strategy used by AIS patients, but allows such strategy to be more precisely adjusted.

In the present study on balance control in seated subjects, similar reaction force data were recorded to those generated by motion in the upright position. The adaptive spatio-temporal responses to self- destabilisation in the seated position observed here were characterised by the slowing of the movement [17], an increase in the excursion of the GRF [5] and an increase in the variability of the parameters analysed [5, 13]. These findings are therefore similar to those obtained during locomotion [13], side-stepping [5], gait initiation [4] and in the standing position [7]. The fact that similar postural control strategies are used in both the seated and upright positions suggests that the lower limbs do not contribute decisively to the development of these strategies. Scoliotic patients' asymmetrical strategic behaviour [3, 22] is due to the body mass displacement caused by the spinal deformation [24]. The mechanical effects of scoliosis influence the patients' postural control processes whether the movement performed involves the whole body or only the spinal segment. The improved stability previously observed in the seated position of scoliotic patients, in comparison with control subjects, suggests that the specific strategies adopted to compensate for the spinal deformation are developed only during dynamic postural tasks performed in the seated position. These dynamic strategies also constitute an adaptive response to sensorimotor deficits [6, 12, 20, 26] and scoliotic patients' impaired spatial perception during dynamic postural control [8]. If the sensorimotor and proprioceptive information used to perform motor activities is perturbed, this is bound to affect the patients' motor strategies [18]. The spinal deformation associated with scoliosis, which involves all three spatial planes, results in the redistribution of body masses, as shown by the asymmetrical ischial thrust recorded in these patients in the sitting position[24] and the asymmetrical GRF exerted during the performance of motor tasks [5, 22]. It was therefore proposed here to increase the inertia of the trunk by adding weights to establish how this parameter affects the patients' dynamic behaviour. Additional weights of this kind did not affect the subjects' balancing strategies when the perturbation was applied in the AP direction. Moreover, these results are directly associated with our specific scoliotic population, which are evaluated by the clinical index of Cobb angle in the frontal plane. An interesting question would be to determine a clinical index to evaluate the scoliotic deformity in the sagittal plane and the possible correlation between these two planes of deformity and the two planes of movement control.

In all the conditions tested, the scoliotic patients' strategies were characterised by a tendency to move forward and toward the concave side of their spinal curvature. Previous studies on seated scoliotic patients have shown the existence of asymmetries between the concave and convex sides of the spinal deformation. On the convex side, the ischial thrust increases [24], the EMG activity increases [14] and larger voluntary lateral movements are made [21]. The present data show in addition that in comparison to the symmetric left/right balance organisation of the control group, the scoliotic subjects (right thoracic curve) take position in the concave direction for balance. This behaviour is associated with a tendency to compensate for the mechanical spinal deformity.

The reaction force data obtained here show that the difference between the ways the two groups coped with AP perturbations focused on the forces exerted in the direction perpendicular to the movement. Scoliotic patients controlled their balance by adjusting the frequency of the forces exerted perpendicular to the movement, as previously described in the case of locomotion [27]. Their balancing strategy was not found to depend on the use of visual cues and was not affected by asymmetric weights attached to the shoulders and the pelvis. Proprioception may be the main sensory mode involved in the development of scoliotic patients' motor strategies in both the sitting and standing positions [23].

The origin of SIA is still very controversial; however, few primary factors seem to be connected to the scoliotic pathology. Neurological troubles based on sensory and spatial perturbation associated with specific myotypologies would establish a favourable context to the appearance of a scoliosis. The scoliotic progress would be more linked to mechanical troubles secondary to the spinal deformation. It is in such specific framework that the patient organises his posture. Such a mechanical effect was confirmed by the use of strategies using re-stabilisation planes associated with controlled segmental levels (pelvis vs. scapula segments).

In conclusion, the results of this study, therefore, show that the way in which scoliotic patients control their seated balance on a seesaw is specific compared to healthy persons. Such specificity is mainly noticeable in the AP direction and consists a larger issue to control balance. In this specific direction (perpendicular to the frontal deformity), these patients did not seem to be affected when the visual cues were abolished, and when asymmetric loads in shoulders and pelvis were applied. The scoliotic patients in the seated position were characterised by larger changes of the GRF, especially with a postural control in the forward and left directions, corresponding to that on the concave side of their spinal curvature. Clinical tests and rehabilitation methods should include assessments of seated patients' spatio-temporal adaptation to the GRF.

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